Modeling agricultural interventions from farm-scale to watershed: The case for Northern Tanzania using Agricultural Policy/Environmental eXtender (APEX) model

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Abstract

Evaluation of agricultural interventions at the farm level is important in order to scale viable interventions that benefit smallholder farmers within the landscape, thus allowing for more effective agricultural policies that can be applied at scale. The Agricultural Policy/Environmental eXtender (APEX) model was applied at two farmland sites in Seloto Village of Northern Tanzania and subsequently at watershed scale. Using a calibrated and validated APEX model, the simulation of two conservation practices, specifically bare contours on sloping farm fields and forages grasses along contours in farming systems (sole and in combination), was evaluated at both the farm scale and watershed scale in Seloto. Four variables (runoff losses, sediment loss, soil moisture storage and crop yield) were compared between field data collected over three years with the two conservation intervention practices. The different farm-scale interventions were then extrapolated and modeled at watershed scale. Differences are presented as percentage reductions compared to a baseline scenario at the inception.

For the field scale, when both contour and forage grasses where compared to the baseline scenario at inception, there was 58% lower runoff, 65% lower sediment, 75% increase for soil moisture storage and 45% increase in crop yield. For the watershed scale, when both contour and forage grasses where compared to the baseline scenario at inception, there was 70% lower runoff, 63% lower sediment, 85% increase for soil moisture storage and 32% increase in crop yield. The substantial decrease in runoff at the watershed scale appears to be associated with increased re-routing of moisture pulses at a greater scale in especially in the landscape patches where conservation interventions were applied. We further demonstrate effectiveness of interventions with measurements of total dissolved solids for stream reaches that had contour terraces soon after rainfall events. The TDS values were substantially lower in areas with contour strips compared to those that did not have. Presence of contour strips depicted that there are modifications introduced pertaining to cumulative infiltration capacity. After calibration and validation, model performances in simulating runoff, sediment load, soil moisture storage and crop yield were considered very satisfactory. Overall, the cumulative and combined effects of field conservation practices are scalable and can help address excess water losses and sediment loading concerns while improving water quality at the landscape level. This permits smallholder farmers to reap the benefits associated with sustainable intensification through improved yields with a lower environmental footprint.

Keywords: Farm-scale, watershed scale, conservation interventions, smallholder farmers, sustainable intensification

Introduction

The APEX (Agricultural Policy/Environmental Extender) model (Williams and Izaurralde, 2006) was developed to assess water quality and other environmental problems in farm or small watersheds in agricultural landscapes (Gassman et al., 2005). APEX has been favored as a modeling tool to assess conservation practices based on its ability to simulate detailed field-scale conservation management operations. APEX can analyze sediment and soil moisture to help evaluate biophysical conservation strategies (i.e., filter strips, terraces, and cover crops). This model has also been applied to different regions to evaluate conservation practices in agriculture (Paudel et al., 2003; Osei et al., 2003; Gassman et al., 2006; Wang et al., 2008, 2009). Thus far, APEX has been used as both a calibrated and uncalibrated model. Estimates using the uncalibrated model may result in larger margins of error compared to the observed data, and therefore less reliable predictions (Saleh et al., 2004; Winchell et al., 2011). Calibrated APEX models, on the other hand, provide greater accuracy and also serve as case studies for helping other users with their calibration processes (Wang et al., 2012). Prior to calibrating and validating a hydrological model, a sensitivity analysis can help rank influential parameters and model options (Yin et al., 2009). Even though the number of studies using APEX is relatively low compared to similar models such as SWAT, which has been extensively used and applied worldwide (Gassman et al., 2007), the most important flow, sediment, and nutrient parameters have been identified in APEX (Yin et al., 2009).

APEX calibration and validation are necessary to improve the model's prediction capability compared to the uncalibrated model, and according to Wang et al. (2011), this can be achieved by following the series of steps and recommendations provided in the available literature. Depending on the variables of interest, APEX provides an array of adjustable parameters. Targeting recurring parameters that have already been identified as sensitive can help facilitate the overall calibration process of the most frequent variables of interest (Wang et al., 2006). To improve APEX's prediction capability for these processes, it is important to further assess the model's performance against observed data. In order to advance our understanding of the impact of agricultural interventions at the watershed level, the present study provides monitoring and modeling results for two different conservation management practices. The specific objectives were to use field-scale monitoring data to tease out the effect of contour terraces and grass strips with forages management practices on soil loss, soil moisture storage, surface runoff and crop yield in order to calibrate, validate, and evaluate APEX modeling of an agricultural landscape for scaling up conservation interventions.

Materials and Methods

2.1 Site characteristics

The study was conducted in the Babati district of Northern Tanzania (Fig. 1), located between the latitudes 3º and 4º south and the longitudes 35º and 36º with an altitude between 1,650 to 2,250 meters above sea level. The Region is a part of the Great Rift Valley and the landscape is characterized by mountains, undulating hills and plains. The precipitation varies with the altitude and ranges from 1200 mm/year in the highlands down to 500 mm/year in the lowlands. The rains are predominantly unimodal with the major rains of the growing season between February and May (Bishop-Sambrook, 2004). Based on description given by Kihara et al 2014, the area is characterized by low fertilizer use and has one lengthy growing season between November and June. Maize is mainly grown as an intercrop with a late maturing pigeon pea (Cajanus cajan L. Millsp.) cultivar. The soils are mainly of volcanic origin and range from sandy loams to clay alluvial soils. The content of organic material and

availability of phosphorus is generally low across the district (Jonsson, 1996). Many farmers in Babati District are agro-pastoralists and the number of livestock in the area is high, livestock rearing constitutes about 35% of the overall land use in the district (Shetto and Owenya, 2007). In some areas, farmers practice traditional post-harvest grazing which is not compatible with systems where soil cover is desired or where contour bunds are practiced.

2.2 Experimental setup and measurements

In May of 2014, field scale measurements were conducted to assess the impact of contour bunds as terraces on soil moisture capture and erosion control with sequential testing of the impact of forages. As indicated in Figure 2, soil moisture content access tubes and soil loss detection boxes were staggered at different slope positions 10 m apart. Along the sole contours and contours with Napier grass, soil moisture measurements were conducted using a Diviner 2000 Probe Series. Measurements were conducted every week over a 2-year period (2014–2015) at the field scale. The Diviner 2000 probe soil moisture data was calibrated gravimetrically under field conditions. For the vertical profile study, measurements were conducted at 0.10 m depth increments to a depth of 1.0 m. Profile stored water was calculated on a depth basis as the product of volumetric water-content and the depth interval (0.10 m) and expressed as millimeters of water. In this study, we present a mean value of soil moisture storage for the 0-50 cm depth range. Erosion assessments were conducted with flexible corrugated iron cubic boxes of 15 cm dimension providing a total cubic volume of 3375 cm^3 as soil traps. Runoff detection was estimated from moisture balances at the field scale while at the watershed scale it was modeled with the APEX tool. Soil loss was estimated periodically by the accumulated volume of soil in calibrated soil traps. Other observations included the dates of planting, dates of harvesting and crop yields along different slope positions, water quality measures above and below the slope positions The control areas had neither sole contour bunds nor forage grass on the contour and these were used to discern soil moisture flux differences, soil loss, runoff and crop yield.

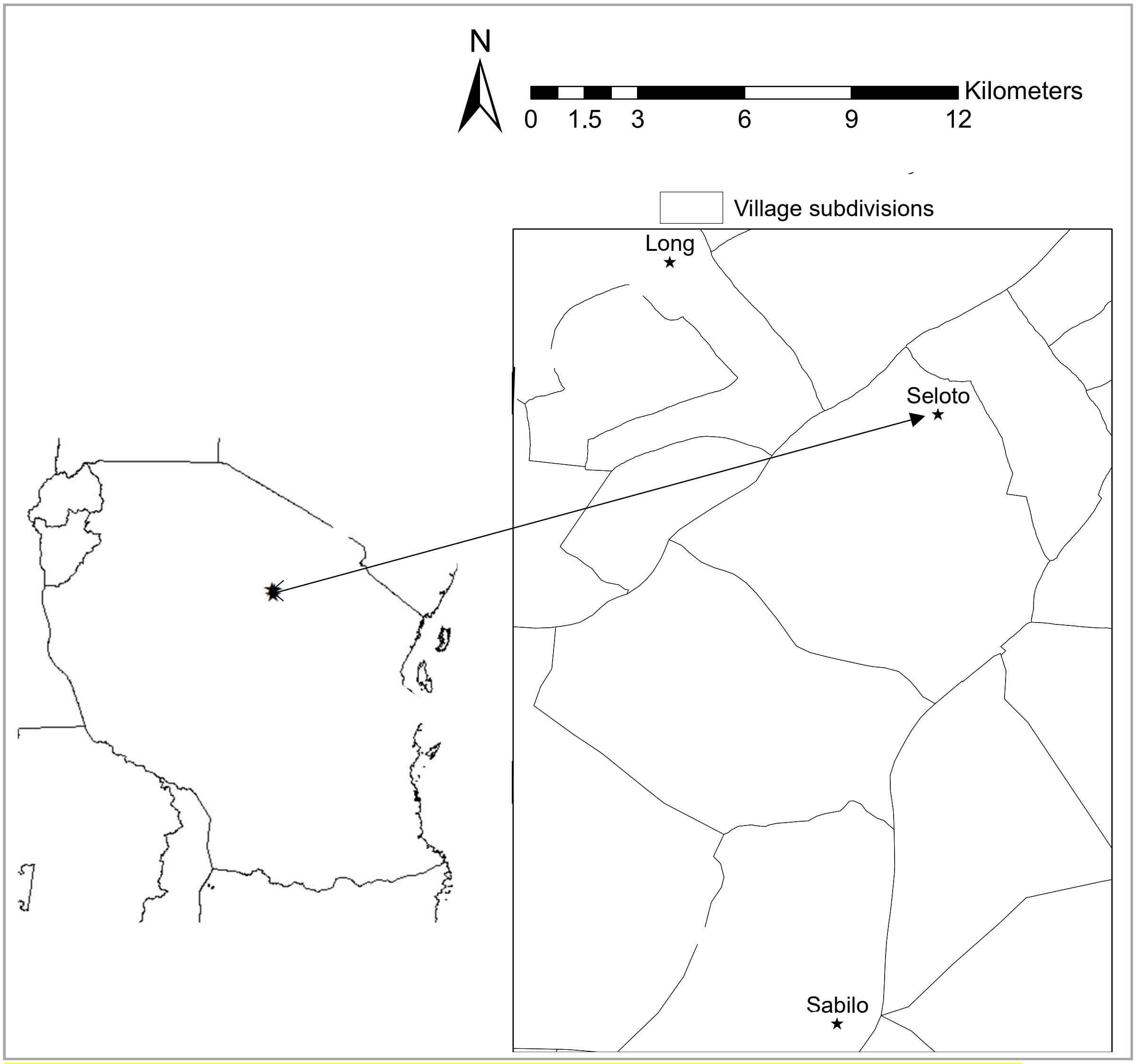
2.3 Micro-climatic data collection for forage water productivity estimates

All micro-climatic parameters were measured using an automated weather station (Spectrum 9 Technologies) at hourly intervals. Rainfall was monitored with a tipping bucket rain gauge (0.5 mm per tip) and evapotranspiration was estimated using the modified FAO Penman–Monteith approach at hourly intervals. Daily reference crop evapotranspiration (ETo) was computed from measured meteorological data; namely solar radiation, air temperature, relative humidity and wind speed. The FAO Penman–Monteith equation (Allen et al. 1998) used for hourly time steps (for a well-watered crop) in this study (Eq. (4) is:

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{37}{T_{hr} + 273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ETo is the reference crop evapotranspiration (mm h^{-1}), Rn the net radiation ($MJm^{-2}\ h^{-1}$), G the soil heat flux density ($MJm^{-2}\ h^{-1}$), T_{hr} is the mean hourly air temperature (°C), (e_s-e_a) the hourly vapor pressure deficit of the air (kPa), Δ the slope of the saturation vapour pressure function

(kPa $^{o}C^{-1}$), γ the apparent psychrometric constant (kPa $^{o}C^{-1}$), u_2 is the average hourly wind speed (m s^{-1}) measured at 2m above the soil surface.



Update map and have coordinates on the side, include stream and outlet features on map
Also indicate areas with infiltration sites, and contours
Figure 1: Location of Seloto village in Babati District, Manyara Region of Tanzania

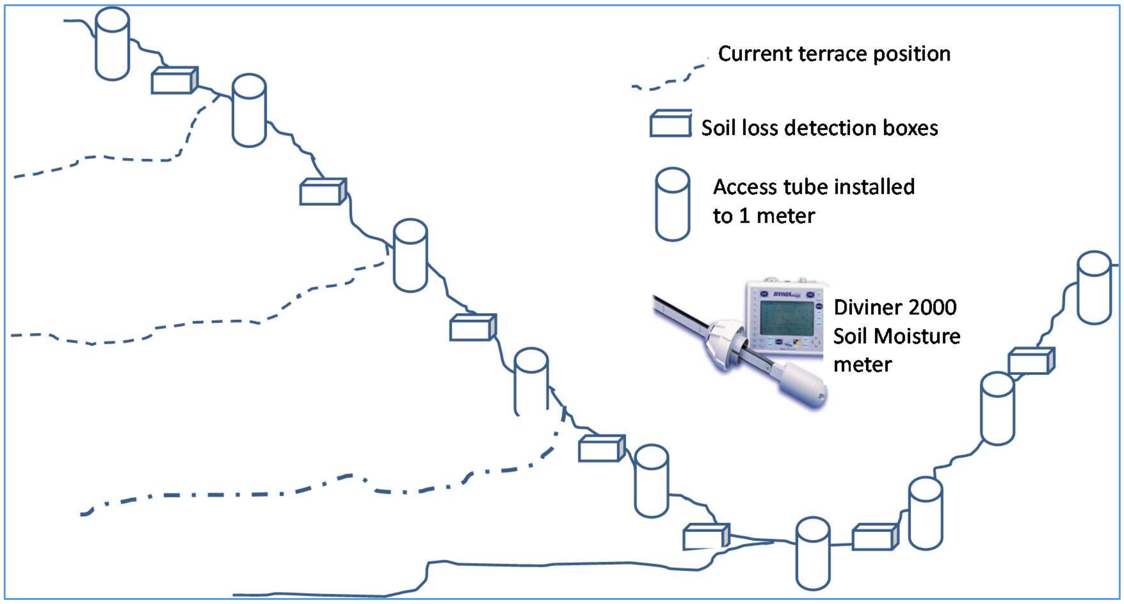


Figure 2: Field scale schematic of interventions and measurements in Seloto village

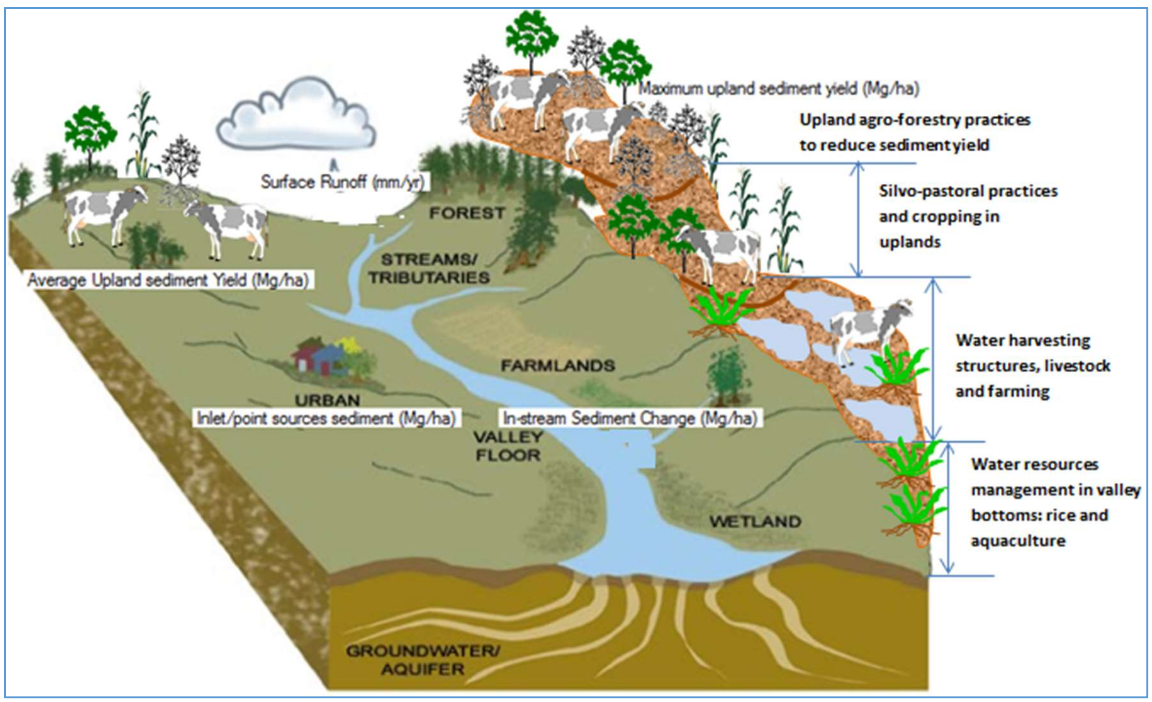


Figure 3. Illustration of farm scale and watershed scale fluxes interactions in association with sediment discharge and other landscape management options. Omit diagram

2.6 Data analysis

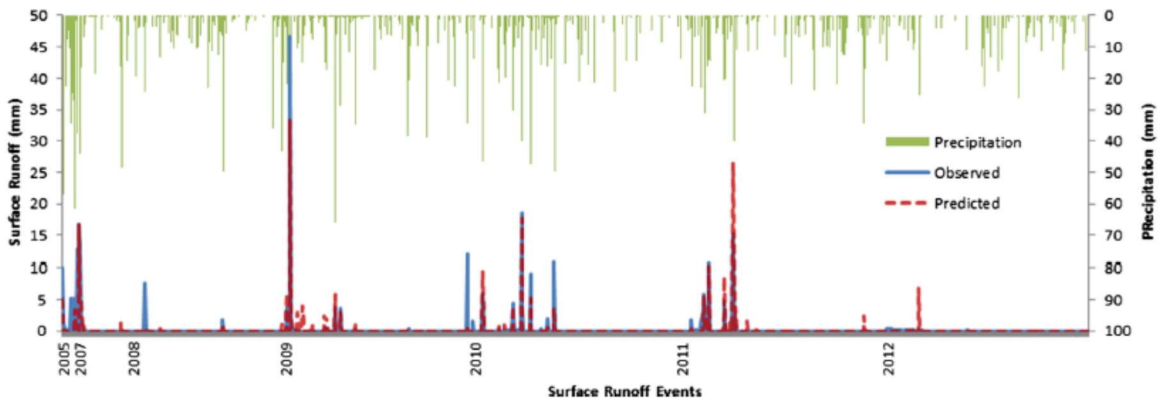
Forage yields, maize yields, runoff, accumulated soil losses and soil moisture storage data were statistically analyzed for two treatments factorial random block design. Since sampling was conducted on the same individuals over time data were analyzed using a repeated measures model (Lindsey, 1993). Two factorial ANOVAs with replication were done to ascertain the interactions between the Napier grass

and contour bunds and test if the mean values for runoff, soil loss, moisture storage and crop yields were significantly different at P= 0.05. A nonparametric Wilcoxon signed-rank test (Wilcoxon, 1945) was used to compare the variables between management systems (with the level of significant difference set to less than or equal to $\alpha = 0.05$). The calibration and validation of APEX surface runoff was evaluated using four quantitative statistical methods: the coefficient of determination (R^2), the Nash-Sutcliffe model efficiency coefficient (NSE) (Nash and Sutcliffe, 1970), the percent bias (PBIAS), and the RMSE-observations standard deviation ratio (RSR) (Nash and Sutcliffe, 1970; Gassman et al., 2010). These are the most frequently used methods to evaluate the calibration and validation of hydrological models, and their corresponding performance ratings have been suggested by (Moriasi et al. 2007). The subsequent calibration and validation of sediment was evaluated using R^2 and NSE. Values above a lower bound of 0.50 and 0.40, respectively, for R^2 and NSE daily comparisons were considered satisfactory for model performance (Moriasi et al., 2007). The score calculation for these methods (R^2 and NSE) was aided by the Web-based Hydrograph Analysis Tool (WHAT) (Lim et al., 2005).

APEX Model input, calibration and validation

APEX version 0806 was used for the present study. The input data required to run the model were collected from various sources. The data used in the geodatabase were collected at the study sites and include elevation, precipitation, air temperature, soil, and land use management. A 30 m × 30 m digital elevation model (DEM) was obtained from ASTER, and soil data were downloaded from the ISRIC website (www.isric.org). Soil information from ISRIC was modified based on soil test data collected under field conditions. Meteorological inputs such as precipitation, solar radiation, relative humidity, and wind speed were collected using weather instruments installed from a nearby weather station (SPECTRUM Technologies). The calibration and validation of daily surface runoff in APEX were done for 2014 and 2015 for each management practice. To simplify the comparison of the calibration and validation processes and results, we evaluated APEX's performance for all the variables over the two year period.

Results



Show **graph of warm up, calibration, validation for both sites based** on met data

Table 1: Bi-annual averages of the field scale statistical results for varying conservation options

Baseline	Event mean	RMSE	R^2	NSE
Surface runoff (mm)	0.02	0.19	0.89	0.52
Soil moisture storage (mm)	0.01	0.16	0.76	0.73
Sediment (t ha-1)	0.03	0.03	0.78	0.45
Contour terraces				
Surface runoff (mm)	0.03	0.23	0.91	0.48
Soil moisture storage (mm)	0.04	0.34	0.82	0.42
Sediment (t ha-1)	0.06	0.05	0.80	0.40
Grass strips				
Surface runoff (mm)	0.02	0.27	0.79	0.55
Soil moisture storage (mm)	0.01	0.18	0.72	0.78
Sediment (t ha-1)	0.03	0.04	0.80	0.41
Contours and Grass strips				
Surface runoff (mm)	0.02	0.21	0.76	0.49
Soil moisture storage (mm)	0.01	0.18	0.82	0.76
Sediment (t ha-1)	0.03	0.02	0.71	0.42

Estimated cost of conducting activity- omit from paper

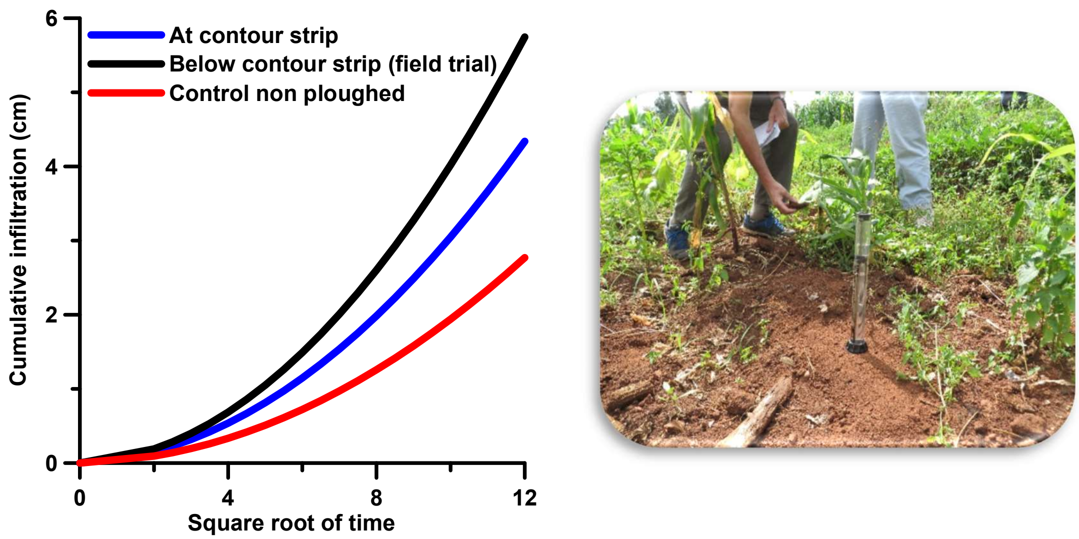


Figure 3. Farm scale monitoring of infiltration trends under varying management options. (add confidence bands)

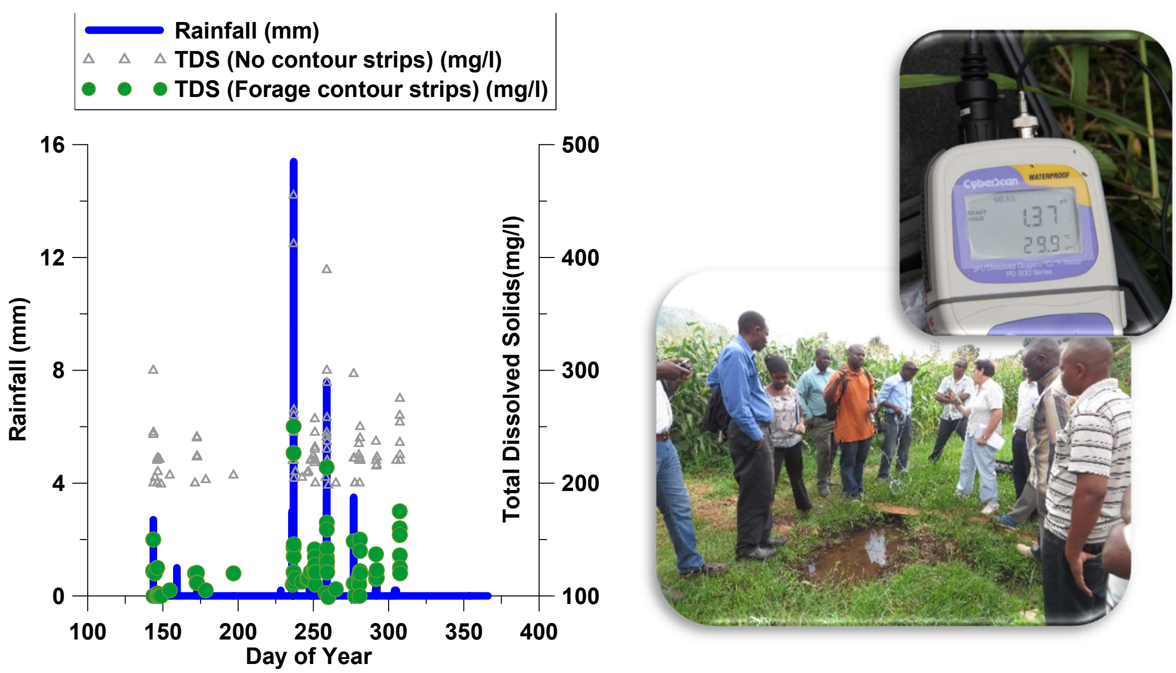


Figure 3. Downstream monitoring of watershed scale water quality under varying management options.

Table 2: Conservation practices on environmental variables and crop yield (annual averages) at the field scale (0.3 ha)

Conservation Practice	Surface runoff (mm)	Soil moisture storage (mm)	Sediment (t ha^{-1})	Maize crop yield (t ha^{-1})
Baseline	37a	54a	0.57a	0.80a
Contour terraces	60b	75b	0.41b	1.20b
Grass strips	74c	87c	0.8c	4.25c
Contours+ Grass strips	88d	94cd	0.2d	4.82c

Consider heat units input and check the yield variations

Nutrient use efficiency considerations

Table 3: Conservation practices on environmental variables and crop yield (annual averages) at the watershed scale (25 ha)

Conservation Practice	Surface runoff (mm)	Soil moisture storage (mm)	Sediment (t ha^{-1})	Maize crop yield (t ha^{-1})
Baseline	142a	100a	4.25a	1.11a
Contour terraces	71b	145b	2.15b	1.24b
Grass strips	58c	202c	2.23c	5.25c*
Contours+ Grass strips	42d	223cd	1.57cd	7.32d*

- Check possibly overestimation?

Economic implications may affect feasibility of uptake specifically labotr

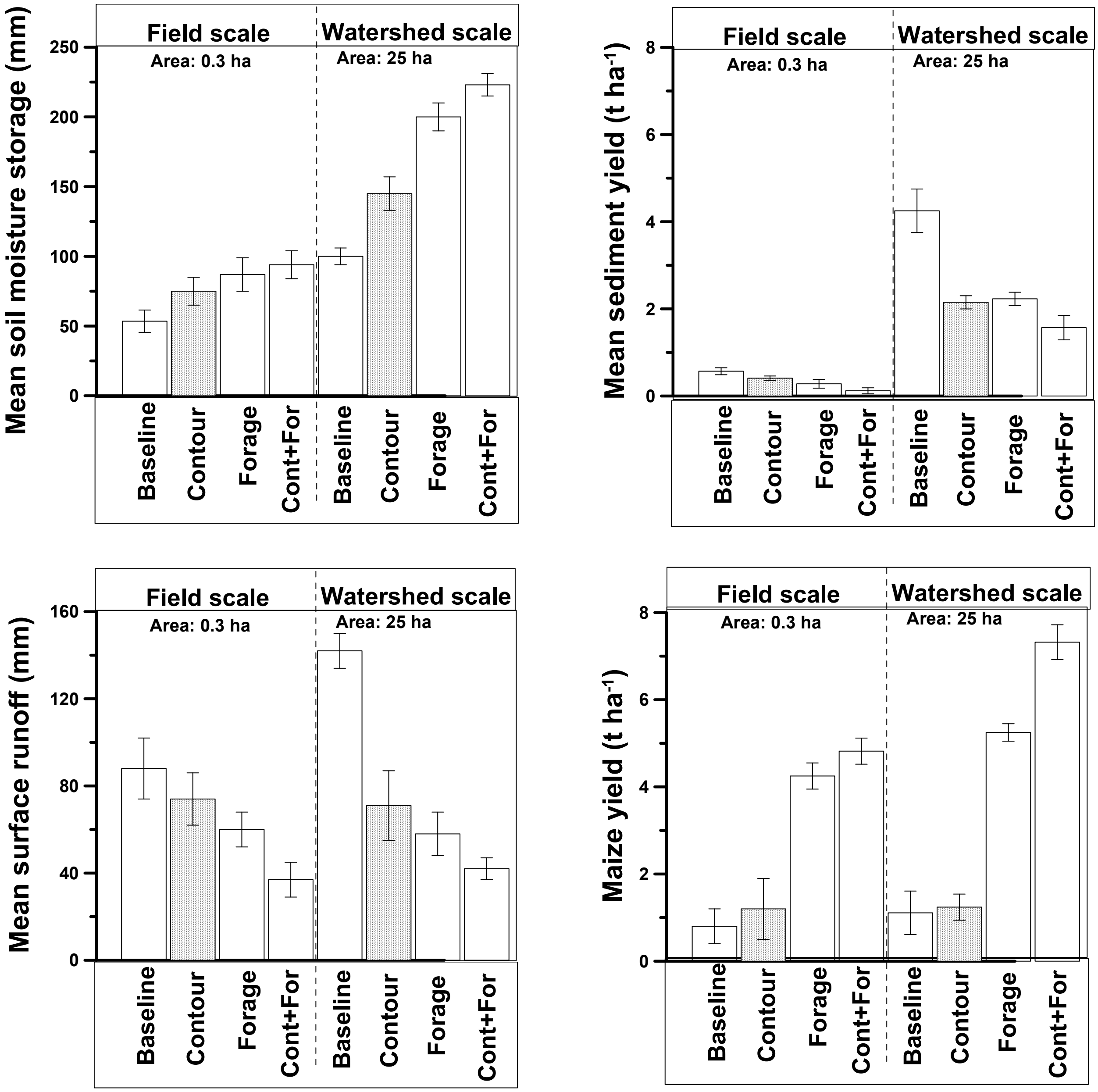


Figure 5. Illustration of farm scale and watershed scale fluxes interactions under varying management options.

(Reconsider representation of yield and provide a secondary axis it should be about 100 times more than the other values)

However, when the conservation practices were combined, the watershed scale revealed that percentage reductions increased for all variables. The total reductions for the combined two practices were 55% for runoff, 60% for sediment, with 58% increase for soil moisture storage while crop yields registered a 30% increment.

Water balance components 2014 and 2015	**Symbol**	**Field scale interventions (mm) of H_20**			
		Contour	**Forage**	**Cont+For**	**Baseline**
Precipitation (Biannual Average)	P	716			
Deep drainage	DD	10.7	5.7	5.7	2.1
Reference evaportranspiration	ETc	561.0	561.0	561.0	561.0
Runoff	RO	14.4	14.9	14.9	45.8
SMS start of cropping season	CSs	30.2	28.1	30.0	27.7
SMS end of cropping season	CSe	9.3	10.1	9.7	7.9
Change in Profile Storage (Root zone)	WBrz	129.8	134.3	134.3	107.0
SMS start of dry season	DSs	9.3	10.1	9.7	7.9
SMS end of dry season	DSe	4.5	9.7	3.7	1.6

Water balance components 2014 and 2015	**Symbol**	**Watershed scale interventions (mm) H_20**			
		Contour	**Forage**	**Cont+For**	**Baseline**
Precipitation (Biannual Average)	P	716			
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Reference evapo-transpiration	ETc	561.0	561.0	561.0	561.0
Runoff	RO	14.4	14.9	14.9	45.8
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SMS end of dry season	DSe	4.5	9.7	3.7	1.6

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Discussions

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Conclusion

The results suggest that single conservation practices may be effective at targeting specific runoff hotspots areas in agricultural landscapes. Among the single conservation practices, cover crops and forages were the most effective at runoff reduction and sediment deposition by about 30%. Results from the combined conservation practices revealed that a systems approach to addressing erosion control within agricultural landscapes would result in a more comprehensive runoff reduction strategy. Compared to the single practices, multi-tiered interventions when extrapolated to the watershed level consistently revealed greater reductions in runoff, and sediment yield but revealed higher soil moisture storage and crop yields. Given the wide array of conservation practices available, there is still need for further evaluation of their combined effect as stacked conservation strategies.

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